

Development Status and Prospects of Industrial Ecology in China

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Abstract In this paper, the research status of industrial ecology abroad is briefly introduced, and the development status of industrial ecology in China is summarized and evaluated, including research content, methods, applications, *etc.* At the same time, combined with the current needs of China's economic-social development, it looks forward to the future development direction and application prospects of industrial ecology. In the coming period, research on green transformation technologies for industrial structure and production methods, carbon peak routes and carbon reduction implementation paths for industrial systems, key technologies for adapting to climate change and achieving carbon peak and carbon neutrality in priority areas, cross regional collaborative technologies for industrial chains, regional energy resource optimization and allocation technologies, efficient industrial agglomeration and collaboration technologies, multimedia composite pollution collaborative governance technologies, collaborative governance technologies for pollution and carbon reduction, multimedia comprehensive governance of multiple pollutants, and empirical theoretical systems of industrial ecology with Chinese characteristics will be the direction of industrial ecology research in China.

Key words Industrial ecology; Development status; Prospect

DOI 10.19547/j.issn2152–3940.2025.04–05.006

Industrial ecology has a history of more than 30 years since its rise. It was first proposed by Robert Frosch and Nicholas E. Gallopoulos of General Motors Corporation in the United States^[1]. Up to now, there are more than 20 definitions in industrial ecology research^[2–3], but the differences in essence are not significant, mostly reflecting its interdisciplinary nature, sustainability, and the relationship between industrial systems and ecological environment. Industrial ecology (IE) is a systematic science that studies the entire metabolic process of natural resources from source, flow to sink in social production activities, organizational management systems, dynamic mechanisms of production, consumption, and regulatory behaviors, control theory methods, and their interrelationships with life support systems. The discipline that studies the interactions and relationships between industrial systems and natural ecosystems is industrial ecology. It is a discipline that serves sustainable development, involving the primary, secondary, and tertiary industries, but not limited to factories. Its scope is very broad, even including mining, agriculture, construction, commerce, waste recycling, and consumers, all of which are closely related to various human activities^[2,4]. The ultimate goal of industrial ecology is to achieve a long-term and sustainable global

economy^[5]. In recent years, the concept of industrial ecology has been applied to varying degrees in many countries and industrial sectors. Especially after entering the 21st century, China's industrial ecology has experienced unprecedented vigorous development. In this paper, the current development status of industrial ecology in China is summarized and evaluated, including research content, methods, and applications. At the same time, based on the current needs of China's socio-economic development, it looks forward to the future development direction and application prospects of industrial ecology.

1 Current research status of industrial ecology abroad

The research on industrial ecology abroad began in the 1980s. In 1989, Robert Frosch and Nicholas E. Gallopoulos of General Motors Corporation in the United States first proposed the concept of industrial ecology through the *Strategy of Manufacturing Industry*, which became the initial symbol of industrial ecology research. In this paper, it was suggested that industrial systems should learn from natural ecosystems, and industrial ecosystems similar to natural ecosystems should be gradually established. In this system, each industrial enterprise is interdependent and interconnected, forming a complex large system. The integrated production methods can be used to replace the simplified traditional

production methods of the past, ultimately reducing the impact of industry on the natural ecological environment^[1].

Since the 1990s, industrial ecology research has entered a flourishing stage of development. In the early 1990s, the American Academy of Sciences held a conference and proposed the basic disciplinary framework of industrial ecology. In 1995, Graedel and Allenby published the first IE book for engineering students. In 1995, IEEE published the *White Paper on Sustainable Development and Industrial Ecology*. In 1997, MIT published the world's first professional journal on industrial ecology. In 1998, the United States Geological Survey (USGS) found that the study of material and energy flow was of great significance for industrial ecology research. In 1998, the Council on Environmental Quality of White House held the first Gordon IE Symposium, specifically discussing the research and development of ecological industry. In 2000, a cross departmental research working group in the United States published a report *Industrial Ecology: Material and Energy Flow in the United States*, which elaborated on the relationship between industrial ecology and material and energy flow. In 2000, the International Society for Industrial Ecology was established worldwide, marking the formal entry of industrial ecology into an organized and systematic research stage.

Since the 21st century, foreign academic and industrial circles have conducted theoretical research and practice on industrial ecology from different perspectives, gradually forming the concept and methodological system of industrial ecology research. Research on industrial ecosystems mainly focuses on the concept, characteristics, operational mechanisms, and ecological efficiency evaluation of industrial ecosystems. A wave of research on industrial ecosystems has gradually emerged, mainly focusing on industrial metabolism, life cycle assessment and design, environmental design, material reduction, ecological industrial parks, ecological benefits, and product oriented environmental policies.

2 Current development status of industrial ecology in China

Chinese scholars began to pay attention to and study industrial ecology research in the late 1990s. In 1999, the Department of Chemical Engineering at Tsinghua University conducted the research on integrated methods for ecological industrial systems with the support of the National Natural Science Foundation of China's key project "Process Integrated Intelligent Method with Economic and Environmental Optimization Objectives". Under the leadership and support of the former State Environmental Protection Administration and some local governments, several ecological industrial parks were planned and constructed. After entering the 21st century, ecological industry has attracted high attention from the government and industry departments in China. In the process of industrial ecology development, the government has always played an important role and played a positive role in promoting it.

In April 2001, Tsinghua University established the Ecological Industry Research Center, actively promoting the theoretical research and practical construction of ecological industry in China. It has achieved certain results in the research of integrated methods for multi-product symbiotic reaction pathways, industrial metabolism analysis methods, integrated methods for substances and energy in ecological industrial systems, sustainable development indicators applicable to industrial systems, and evolution process of ecological industrial systems and its influencing factors. It has important guiding significance for the analysis, integration, and regulation of ecological industrial systems^[6]. In October 2001, the first international seminar on industrial ecology in China was hosted at Northeastern University. In 2002, the State Environmental Protection Administration approved the joint establishment of the "National Key Laboratory of Environmental Protection Ecological Industry" by Northeastern University, the Chinese Academy of Environmental Sciences, and Tsinghua University. This is the first key laboratory in the field of industrial ecology research in China. In 2002, the Guigang National Ecological Industry (Sugar) Demonstration Park passed the demonstration meeting hosted by the State Environmental Protection Administration and other departments. This is the first industrial park in China to be planned and constructed according to the ecological industrial park. Subsequently, some domestic ecological industrial demonstration parks with unique characteristics, such as the Nanhai National Ecological Industrial Park, Tianjin Economic and Technological Development Zone Ecological Industrial Park, and Yantai Development Zone Ecological Industrial Park, have also begun to be constructed. In 2003, the Engineering and Materials Science Department and the Management Science Department of the National Natural Science Foundation of China jointly initiated a basic research project on major issues in the field of industrial ecology, titled "Ecological Management Mode and Evaluation System of Steel Industry". This marked the beginning of industrial ecology entering the main battlefield of scientific research from outside of orthodox scientific research^[3].

With the continuous development of theoretical basis, technical methods, and management applications of industrial ecology research, domestic industrial ecology research and practice have achieved initial results since 2000, forming a theoretical and methodological system that is both in line with the mainstream of international research and China's national characteristics (Table 1)^[2]. The focus was on theoretical research in industrial ecology, research on industrial ecological processes and mechanisms, management practice research, and benefit analysis. In the early stage, the research mainly focused on the theoretical framework of industrial ecology^[7-12] and process mechanism characteristics^[13-17]. In recent years, more research has been conducted on management practices^[18-22] and benefit studies^[23-31] of industrial ecology, mainly focusing on methods, models, indicators, and influencing factors of industrial ecological benefit assessment^[3].

Table 1 Overview of industrial ecology research in China since the 21st century

Researcher	Time	Research content	Research direction
Zhang Wenhong	2000	The openness, complexity, evolution, and emergence of industrial ecosystem fully demonstrated that it is a typical open and complex giant system. She applied the idea of a comprehensive integrated research system to integrate intelligent control technology, response curve method, and experimental design into a nonlinear multi-objective decision support system, proposing a new method for designing industrial ecosystems	Theoretical framework of industrial ecology
Wang Qian, Zou Xinqing	2001	Starting from four dimensions: government, enterprise, market, and public, the driving factors affecting the development of industrial ecology were identified. It indicated that the primary driving force for industrial ecology construction was guiding policies, and the important support was regulatory policies	Process mechanism of industrial ecology
Wu Wei	2002	It should strengthen the control and management of industrial ecosystems, and propose methods such as decentralized and hierarchical control	Management and practice of industrial ecology
Qu Jingda, Han Tianxi	2002	The stability of network members in the industrial ecology was mainly reflected in the supply and demand relationship between members and the efficient connection of industrial spatial organization. The relationships between network members of industrial ecology were complex and diverse. Maintain the openness of the industrial ecological network and analyze from the aspects of structural dimension, technical conditions, and external dimensions that the industrial ecological network has good economic and environmental benefits	Research on the network relationship of industrial ecology
Chen Dingjiang	2002	Taking Zaozhuang as an example, an industrial ecosystem model was constructed, and mathematical nonlinear principles were applied to analyze the industrial system	Theory and practice of industrial ecological parks
Tang Huilan	2003	The basic characteristics of industrial ecosystems were analyzed from different perspectives, construction strategies, methods, and principles were proposed, and a relatively advanced theoretical framework for industrial ecosystems was built	Theoretical framework of industrial ecology
Hu Shanying	2003	System integration issues within industrial ecosystems were explored deeply, and effective methods and approaches for the integration and circulation of materials, energy, information, <i>etc.</i> in industrial ecosystems were discovered	Theory and practice of industrial ecological parks
Wang Hong, Ye Xun	2003	The driving mechanism of enterprises in industrial ecological parks was studied, the socio-economic attributes and key constraints of enterprises in industrial ecological parks were analyzed, and the process of enterprise participation in industrialization was pointed out. The requirement of industrial ecology was the fundamental essence of ecological park construction, which can enable enterprises to achieve economic and social value. This was the driving force for enterprises to participate in the construction of industrial ecological parks	Process mechanism of industrial ecology
Li Kun, Wei Xiaoping	2003	By utilizing the characteristic laws of nonlinear coherence, system openness, departure from equilibrium structure, and breakthrough the "threshold" mutation, the system dynamic factors that affect the construction of industrial ecology were pointed out in response to the evolution of industrial systems	Process mechanism of industrial ecology
Guo Li, Su Jingqin	2004	The Logistic model in biology was used to describe the symbiotic relationships among different populations, revealing the fact that industrial symbiosis carried operational risks, and analyzing the stability conditions of different industrial symbiosis models	Management and practice of industrial ecology
Dai Tiejun, Lu Zhongwu	2005	When calculating the ecological efficiency of high energy consuming enterprises such as steel, three indicators of enterprise ecological efficiency were adopted: resource efficiency, energy efficiency, and environmental efficiency	Industrial ecological efficiency
Qiu Shoufeng	2007	An evaluation index system of ecological efficiency was established based on resource consumption and environmental impact. Resource efficiency includes three aspects: labor, energy, and water. Environmental efficiency includes wastewater, exhaust gas, and solid waste	Industrial ecological efficiency
Chai Lihe, Huo Cuihua	2007	The simulation and analysis methods for the structural evolution of ecological industrial systems were studied	Process mechanism of industrial ecology
Jin Yonghong, Ci Xiangyang	2008	The industrial symbiosis chain network structure model of ecological industrial park was constructed	Theoretical framework of industrial ecology
Yang Wenju	2009	Based on economic output data, using the ecological efficiency analysis method of data envelopment analysis, the endogenous weights of various environmental pressure indicators were obtained, thereby obtaining the maximum relative ecological efficiency obtained by each unit	Industrial ecological efficiency

(To be continued)

(Continued)

Researcher	Time	Research content	Research direction
Wang Enxu	2011	The input-output index system of ecological efficiency was formed through the super efficiency DEA model, and the ecological efficiency of 30 regions in China was evaluated and analyzed	Industrial ecological efficiency
Miao Zehua	2012	It was believed that industrial enterprises were important units of the social-economic-natural complex ecosystem, and can also follow the principles and principles of symbiosis. Through the design and construction of symbiosis mechanisms, symbiosis and circulation between enterprises can be achieved	Process mechanism of industrial ecology
Zhao Jun	2014	The construction of the bioenergy industry ecosystem was studied, the organizational form and boundaries of the system were analyzed, and the various functions of the system were explored	Theoretical framework of industrial ecology
Lu Yanqun	2017	The VRS-DEA method was used to measure the industrial ecological efficiency in thirty provinces of China from 2005 to 2014. Based on this, spatial econometric model was used to examine its influencing factors	Industrial ecological efficiency
Li Chengyu	2018	Using DEA-BCC method and combined with Malmquist method, the industrial ecological efficiency in thirty provinces in China from 2006 to 2015 was measured in both time and space dimensions	Industrial ecological efficiency
Zhou Xudong	2019	The industrial ecological efficiency and its changing characteristics in 14 prefecture-level cities (prefectures and regions) in Xinjiang were evaluated using the super efficiency DEA model, and Tobit regression analysis was conducted	Industrial ecological efficiency
Liu Ye	2019	Thirteen industrial diversity indicators were selected, including four indices transplanted from the biodiversity index and nine indices specially constructed for specific purposes, to analyze the spatial distribution pattern of industrial ecosystem diversity in Shandong Province. Exploratory spatial data analysis was used to analyze the spatial correlation of industrial ecosystem diversity among counties	Research on the network relationship of industrial ecology
Zhou Xin	2019	Research on industrial ecological agglomeration and its influencing factors in the upper reaches of the Yangtze River	Process mechanism of industrial ecology
Qian Li	2020	Research on the operational performance and green innovation mechanism of industrial ecological economic system	Management and practice of industrial ecology
Cong Rijie	2020	Regional carbon emissions and its impact on the operational efficiency of industrial ecosystems were studied using spatial statistical analysis method, system dynamics theory, DEA method, <i>etc.</i>	Industrial ecological efficiency
Huang Yang	2021	The industrial ecological efficiency of 29 provincial regions in China from 2012 to 2015 was analyzed and studied based on the PARETO improved two-stage DEA cross efficiency model	Industrial ecological efficiency
Geng Pengxu	2021	The ecological chain of coal mining industry based on industrial ecology was studied	Management and practice of industrial ecology

3 Prospects for the development of industrial ecology

As a developing country, China's extensive industrial growth has made tremendous contributions to economic development since the reform and opening up 40 years ago. After the 21st century, the research results of industrial ecology have been applied in the development of China's industry, and the process of combining industrial development with ecological benefits. Industrial development has achieved remarkable results, including good economic, social, and ecological benefits. A complete industrial system has become a national treasure. But currently, China's industrial development has entered a bottleneck period. The industrial structure dominated by heavy chemical industry, the energy structure dominated by coal, and the situation of relying on energy resource processing and conversion to drive economic development are difficult to fundamentally change in the short term. The regional environmental pressure caused by resource and energy consumption will continue. With the construction and production of energy projects or the release of production capacity during the "14th Five-year Plan" period, the pressure on greenhouse gas and pollutant emission control will remain severe.

Due to the late start of industrial ecology research in China,

the breadth and depth of current research are still relatively limited. Based on the national characteristics of China as a developing major country, the study of industrial ecosystem with Chinese characteristics will be a key area of research in the future of industrial ecology in China. On the one hand, China is a major manufacturing country in the world. In terms of industrial systems, China has 41 major categories, 207 medium categories, and 666 subcategories, making it the most complete industrial system in the world. China's manufacturing industry covers all types of industries, making it the only country in the world with all industrial categories. The comprehensive advantages of China's industrial chain are not only irreplaceable by any country, but will also be further improved with the addition of new industries. Therefore, China's industrial ecosystem is the best case for conducting industrial ecology research. On the other hand, given the complexity and diversity of China's industrial system, various resource and environmental constraints, as well as the constraints or synergistic effects between different industries, inevitably face more complex and unpredictable pressures and challenges. Therefore, there is still a long way to go to accelerate the improvement of China's industrial ecology research level.

In the coming period, based on China's national conditions,

continuously improving the theoretical research and practice of industrial ecology from the perspectives of basic theory, policies, and applications is the direction of research and development in industrial ecology in China.

(1) As a new form of innovation from the perspective of ecological civilization, green innovation is the key to breaking through current resource and environmental constraints, and an important driving force for promoting the green transformation of industrial ecosystems^[32]. Therefore, the research on the green transformation of industrial structure and production methods will become the main direction. It should explore the collaborative promotion mode of clean production areas, and accelerate the research on clean substitution of fuel raw materials and clean low-carbon transformation technology for key industries.

(2) The "14th Five-year Plan" period is a critical and window period for China to address climate change and achieve its carbon peak goals, as well as a key five-year period for the industrial sector to achieve green and low-carbon transformation. Green and low-carbon development is the direction of technological revolution and industrial transformation in today's era, and green economy has become the commanding height of global industrial competition. The pressure to reduce greenhouse gas emissions is unprecedented, and it poses significant technological challenges to achieving carbon peak and neutrality goals as scheduled and addressing climate change. Therefore, the carbon peak route and carbon reduction implementation path of the industrial system, adaptation to climate change in key areas, key technologies for carbon peak and carbon neutrality, green and low-carbon technologies such as carbon neutrality, carbon dioxide removal, and low-cost utilization may be the research hotspots during the "14th Five-year Plan" period.

(3) At the same time, green and low-carbon layout optimization and regulation strategies in key regions such as Beijing – Tianjin – Hebei, Yangtze River Delta, and Guangdong – Hong Kong – Macao Greater Bay Area, as well as cross regional collaborative technology in industrial chains, regional energy resource optimization and allocation technology, efficient industrial agglomeration and efficient collaborative technology, will also be important research directions for industrial ecology management and application.

(4) Faced with the complex ecological and environmental problems in China's industrial system, such as the overlapping of new and old pollutants, and the emergence of regional systemic ecological risks, the structural, fundamental, and trending pressures on China's ecological environment will continue to exist for a long time. Therefore, it is also another focus of future industrial ecology research by conducting research on multimedia composite pollution collaborative treatment technology, pollution reduction and carbon reduction collaborative treatment technology, cross media comprehensive treatment of multiple pollutants, and restoration and treatment technology for mountain, water, forest, field, lake, grass and sand systems.

(5) While aligning with international standards, it should comprehensively study the important phenomena of industrial development in China's industrialization process, break down barriers

between technical science, ecology, and economics, and establish a empirical theoretical system of industrial ecology with Chinese characteristics, comprehensively serving the practice of industrial ecology in China^[33], and providing research demonstrations for the development of international industrial ecology.

Therefore, the future research in the above fields of industrial ecology in China has important theoretical value and practical significance for implementing the innovation driven development strategy, promoting sustainable development of Chinese industry, taking the path of green industrialization, and deepening the construction of ecological civilization.

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ies, enhance spatial image, reshape spatial vitality, improve urban public services, and promote high-quality urban development. In the future, riverside landscape design needs to focus on intelligence and sustainability, continuously optimize functions and experiences through dynamic monitoring and user participation, and create more livable, healthy, and culturally rich public spaces for urban residents.

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Acknowledgement

Meteorological and Environmental Research [ISSN: 2152 – 3940] is a comprehensive meteorological and environmental scientific journal, and contains strong technicality and high orientation in China, being published bimonthly in Rhode Island, USA. It has been included by UPD, Chemical Abstracts, CABI, Cambridge Scientific Abstracts, EBSCO, AGRIS, EA, Chinese Science and Technology Periodical Database, Library of Congress (United States), and CNKI.

Fortunately, for the contributions of all authors and readers to *Meteorological and Environmental Research*, it has been published successfully for fifteen years. And we, all members of the editor office of *Meteorological and Environmental Research*, appreciate all help and assistance from you in the publication of our journal.